Quantum Atom Interferometer Gravity Gradiometer in Space

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The work was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

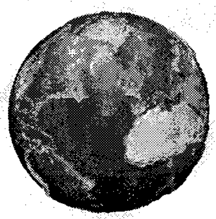
Gradiometer and Its Applications

Description: A gravity gradiometer is a fundamental device for characterizing gravity fields by measuring the acceleration (or force) difference of test masses separated by a given distance.

Gravity gradient basics:
Gravity gradient is a tensor, $\propto m/R^3$.
Unit: $ms^{-2}/m = s^{-2}$, or $1\ E$ (Eötvös) $= 10^{-9}\ s^{-2}$.
On the Earth surface: about *3000 E.*

MOTIVATIONS

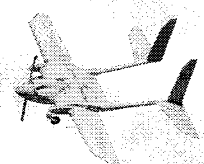
Applications for NASA/JPL



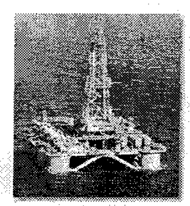
Remote sensing of surface/subsurface density profile by 3D mapping of gravity in Earth and Planetary Sciences.

Gravitational measurement for testing theory of general relativity in Space Science and Fundamental Physics.

Applications for DoD and Commercial



- Large underground structure detection
- Covert navigation



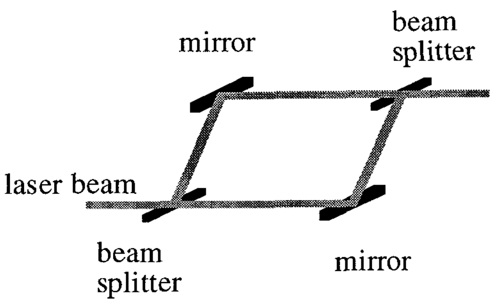
Oil/mineral exploration.

Atom-Wave Interferometer

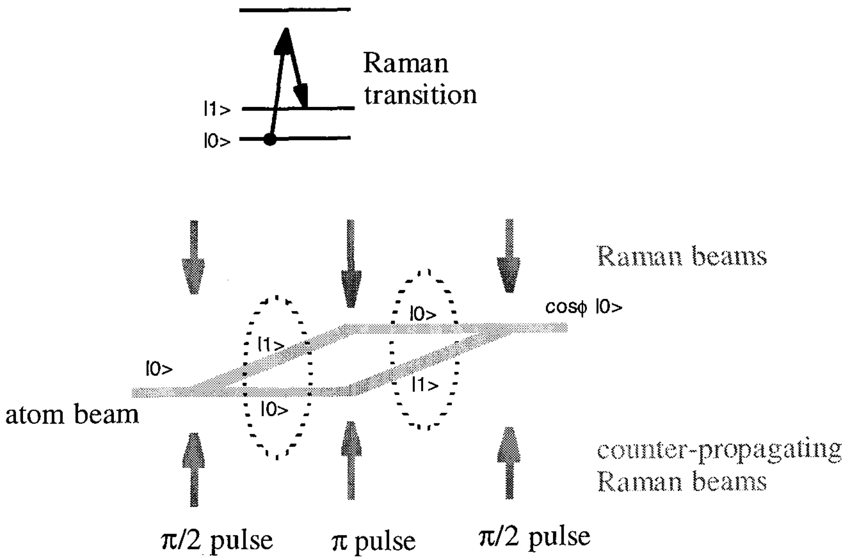
Quantum particle-wave duality 

Understanding Atom-Wave Interferometer

a) optical Mach-Zehnder Interferometer

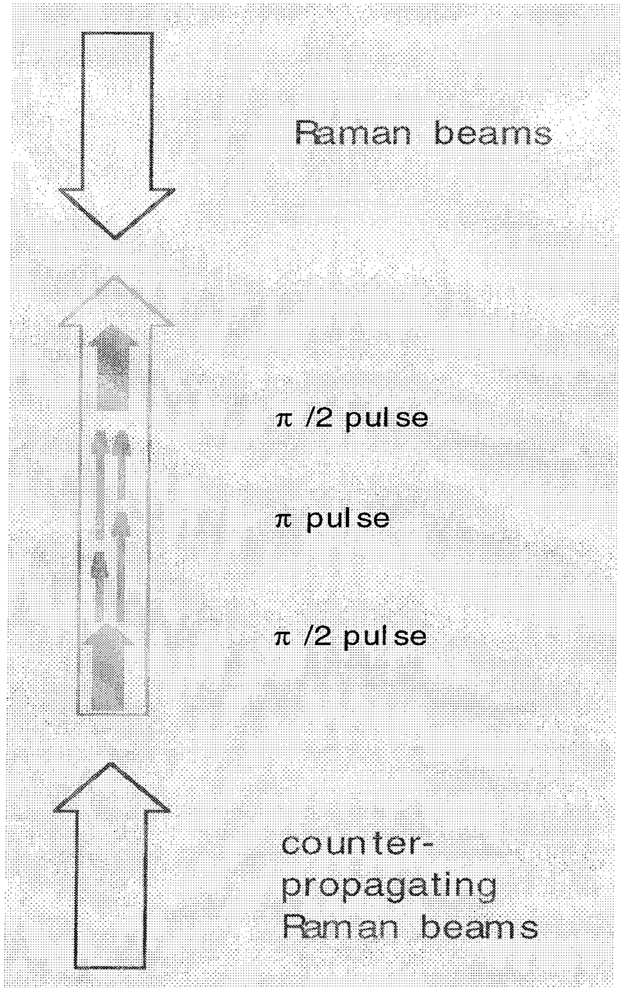


b) atom-wave MZ interferometer



The enabling technology: laser cooling and atom manipulation

Atom Interferometer as Accelerometer



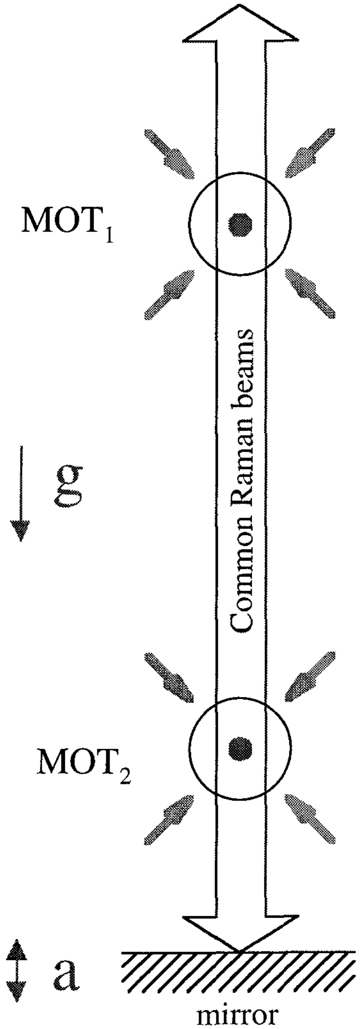
$$\Phi = \phi1 - \phi2 + \phi3 - \phi4 = \mathbf{k_e a T^2} + 2\Delta\omega T$$

For interferometer with counter propagating laser beams, k_e=2k, $\Delta\omega$=0 can be arranged to be zero, $\Phi = 2\,\mathbf{k\,a\,T^2}$.

Discussion:

1) ϕ is independent of initial velocity of atoms.
2) $\phi \propto T^2$, slow atoms allow longer interrogation time, thus higher sensitivity.
3) The acceleration measured is relative to the Raman beam reference frame.
4) The Raman pulses are related to atomic clock technology, but with Doppler sensitive transitions.
5) Expected sensitivity using Cs of T = 1 second interrogation time with S/N=1000:1 is
   10^{-11} g/$\sqrt{\text{Hz}}$

Atom Interferometer Based Gravity Gradiometer



$\Phi_1 = 2k(g_1+a)T^2$

$\Phi_2 = 2k(g_2+a)T^2$

$$\boxed{\Delta\Phi = 2k\,(g_1 - g_1)\,T^2}$$

The common reference acceleration has been cancelled out[(1)], which allows the gradiometer to be used on moving platforms such as spacecraft.

The common-mode suppression has been demonstrated to be greater that 150 dB ! [(2)]

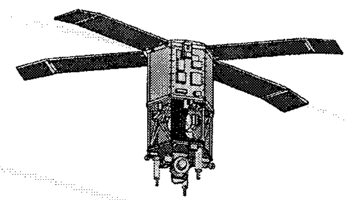
(1) M. J. Snadden et al. PRL **81**, 971 (1998).
(2) M. Kasevich, Private communication (2000).

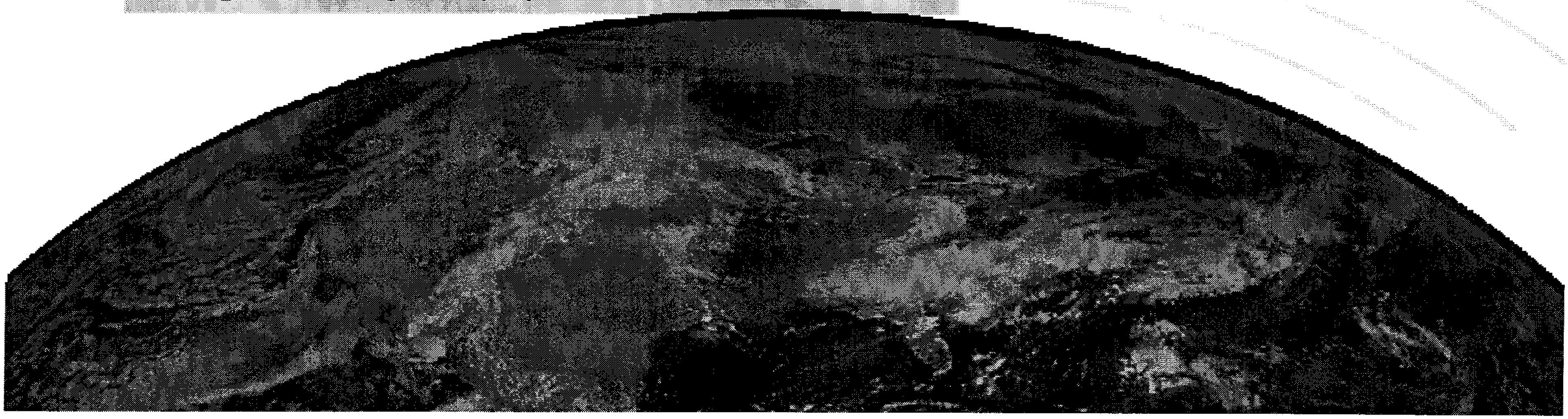
Gravity Gradiomter in Space

Advantages in space (μg environment):

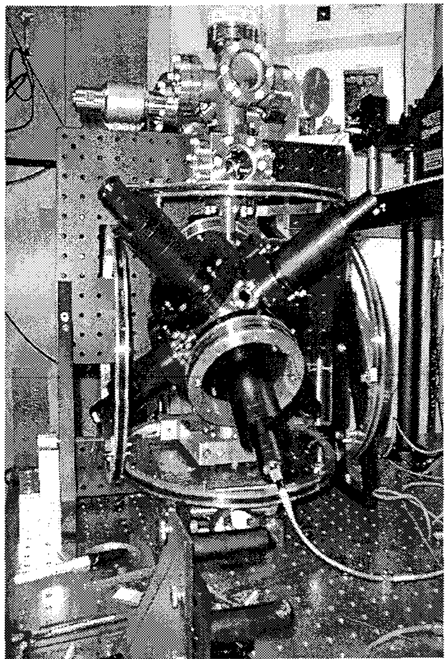
- True slow beam application, no launching and associated Doppler shifts.
- Very long interrogation time possible, which leads to extremely high sensitivity.
- Multi-axis sensing possible, allowing full tensor mapping.
- Longer baseline operation possible (> 10m).
- Helps reducing many systematic effects.

Performance expectation with demonstrated technology, assuming 10 sec. Interrogation time, SNR > 1000:1, and 10 m baseline separation:
$< 10^{-4}$ E/$\sqrt{\text{Hz}}$;
$< 10^{-5}$ E in a day, $< 10^{-6}$ E in a year.

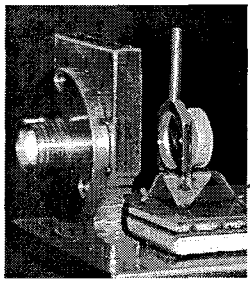


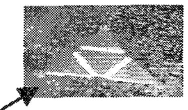


Towards Space-Flyable Atom Interferometers



Current lab gradiometer
atomic fountain at JPL

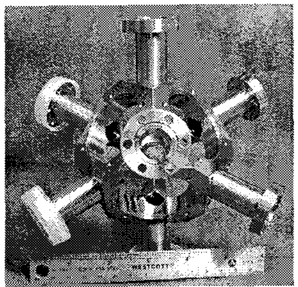




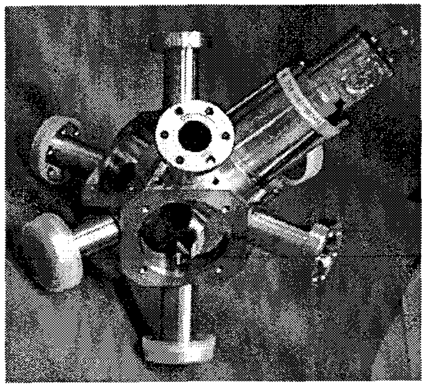
Laser welding
approach

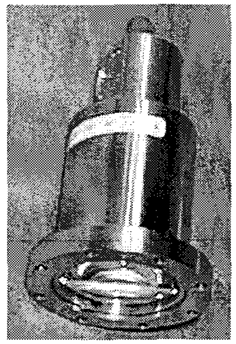
Hardware Design and Implementation

Space MOT Technology

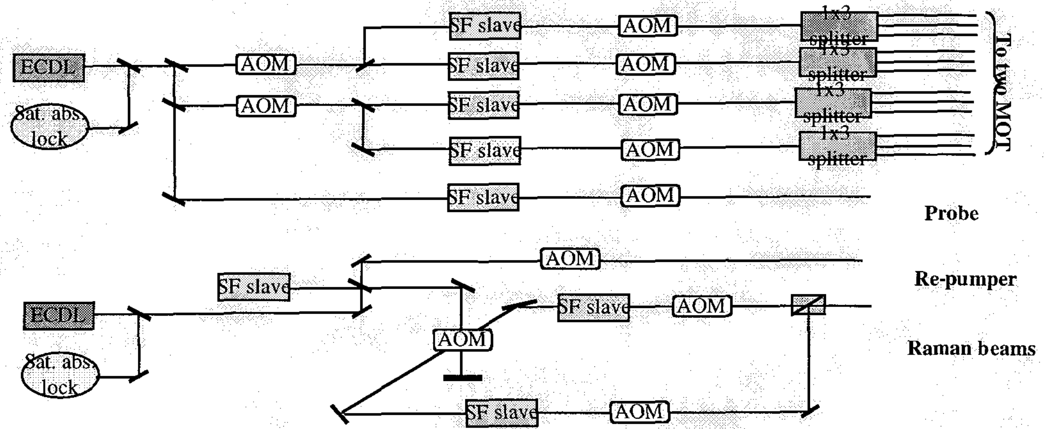


Titanium Source Chamber
and laser beam collimator
Courtesy of PARCS





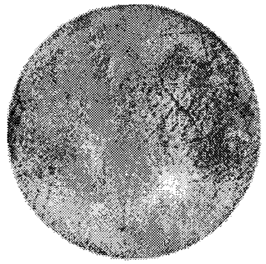
Laser system block diagram(injection-locked diode laser approach):



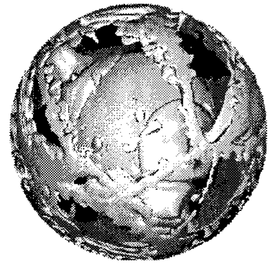
Surface Mass Distribution and Climate Monitoring

Earth and Planetary Interiors

- **Lithospheric thickness, composition**
- **Lateral mantle density hetrogeneity**
- **Deep interior studies**
- **Translational oscillation between core/mantle**



Jupiter's Moon Europa
"hidden Ocean beneath?"

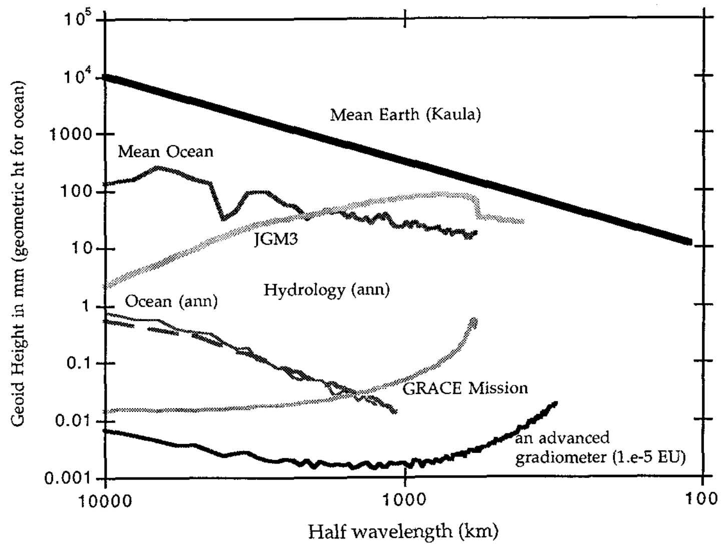


3-D simulation of compressible mantle convection

Earth and Planetary Climate Effects

- **Surface and ground water storage**
- **Oceanic circulation**
- **Tectonic and glacial movements**
- **Tidal variations**

Beyond *GRACE* capability

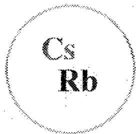


Fundamental Science: EEP and Spin-Gravity Coupling

Similarly to an atom-wave interferometer gravity gradiometer, one can instead design an experiment to simultaneously measure the accelerations of two co-located atom ensembles of different species such as Rb and Cs for Einstain's Equivalence Principle test[1], or different atomic spin states for searching spin-gravity coupling. As the measurements are simultaneous and co-located, many potential common-mode systematic errors are rejected, making high precision tests possible.

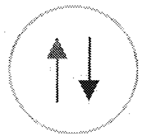
Unlike in a gradiometer, the co-located atom ensembles experience exactly the same gravitational potential, continuous integration is possible on an orbiting satellite.

EEP Test



$\Delta g = g_{Cs} - g_{Rb} = ?$

Spin-Gravity Coupling



$\sigma \bullet g = ?$

Expected differential acceleration measurement sensitivity in a flight experiment:

$< 1 \times 10^{-13}\ g / \sqrt{Hz}$.

and reaches an accuracy of $< 10^{-16}$ g in 6 months.

Current torsion balance test is at 1×10^{-12} level.

Compared to other proposed flight EEP test experiments,

1) identical atomic proof mass
2) laser distance measurement
3) no cryogenics and no moving parts

[1]Currently, there is a joint Yale/JPL proposal for an EEP test experiment

Challenges and the Future

FACING THE CHALLENGE:

To achieve desired sensitivity and stability:

- Higher S/N ratio through increasing number of atoms and generating colder atom source;
- Extremely good understanding and control of systematic effects including Stark shifts, Zeeman shifts, vibration noise, rotation noise, laser alignment errors, and ultra-cold collision phase shifts;
- Engineering reliable system package for long-term space operation.

FUTURE IMPROVEMENT

- Multiple pulse beam-splitting technology
- Use of ultra-cold atoms and Bose-Einstein condensate
- Use of coherence matter-wave and quantum number states

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